Biodegradation of phenol and m-cresol in a batch and fed batch operated internal loop airlift bioreactor by indigenous mixed microbial culture predominantly *Pseudomonas* sp.

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**A B S T R A C T**

An internal loop airlift reactor (ILALR) is developed and studied for biodegradation of phenol/m-cresol as single and dual substrate systems under batch and fed batch operation using an indigenous mixed microbial strain, predominantly *Pseudomonas* sp. The results showed that the culture could degrade phenol/m-cresol completely at a maximum concentration of 600 mg l\(^{-1}\) and 400 mg l\(^{-1}\), respectively. Batch ILALR study has revealed that phenol has been preferentially degraded by the microbial culture rather than m-cresol probably owing to the toxic effect of the later. Sum kinetic model evaluated the interaction between the phenol/m-cresol in dual substrate system, which resulted in a high coefficient of determination (\(R^2\) value >0.98). The fed batch results showed that the strain was able to degrade phenol/m-cresol with maximum individual concentrations 600 mg l\(^{-1}\) each in 26 h and 37 h, respectively. Moreover for fed batch operation, degradation rates increased with increase in feed concentration without any lag in the degradation profile.

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1. Introduction

Environment pollution, especially with the hazardous and recalcitrant toxic chemicals, is one of the major problems faced by the developing countries like India. Phenol and m-cresol are two such toxic pollutants discharged into the environment by various industrial operations, which include petroleum refineries, petrochemical, textile, dying, phenolic resin manufacturing, glass fiber units, varnish industries and smelting related to metallurgical operations (Juang and Tsai, 2006; Yan et al., 2006; Bai et al., 2007). These compounds have high stability, high toxicity and they are carcinogenic in nature. They cause considerable damage and threat to the ecosystem. Also they are aromatic organic compounds, which are rather resistant to natural biodegradation and continue to persist in the environment for a longer time (Juang and Tsai, 2006). Elimination or degradation of such recalcitrant chemicals from the wastewater completely has thus become a challenging task for the scientific community working in the related field. As opposed to the conventional treatment techniques such as coagulation, adsorption on activated carbon and advanced oxidation process; biological treatment as activated sludge process has shown a better performance for treating such recalcitrant compounds for complete elimination from wastewater (Ryan et al., 2005; Bai et al., 2007).

However, the successful applications of biological method for wastewater treatment often rely on the type of reactor system employed. For example, biological treatment of phenolics in conventional activated sludge process fails to achieve high efficiency in removing phenolics at high loading. In present scenario, airlift bioreactors (generally employed for fermentation) have become popular, in degrading such organics by using suitable microbes. The major advantage of airlift bioreactors is that they do not need any mechanical agitation. It requires only aeration which serves both as oxygen supply as well as mixing with low energy input for its operation (Annetton et al., 2006). In general, an internal loop airlift reactor is essentially a bubble column with a baffle or a draught tube separating the rising fluid from the sinking fluid. It is simple in construction and operation, where fluid circulation occurs in a defined cyclic pattern i.e., through a loop of conduits. When compared to conventional reactors, such as stirred tanks or bubble columns, shear stress can relatively be constant and mild throughout the ILALR. This is favorable to microbial growth (Kanai et al., 1996). These advantages explain the growing attention on airlift reactors in the recent times (Camarasa et al., 2001; Couvert et al., 2004; Sun et al., 2006).

In recent years, attempts were made to evaluate the performance of ILALR towards adoptability for wastewater treatment; some of them are reported here. Jajuee et al. (2007) studied the kinetics of p-xylene and naphthalene as single and mixed substrate in batch airlift immobilized bioreactor. They varied the p-xylene concentration between 15.4 mg l\(^{-1}\) and 75 mg l\(^{-1}\) and naphthalene...
concentration between 4 mg l\(^{-1}\) and 16.5 mg l\(^{-1}\), respectively, and correlated the experimental results with Monod kinetic model. Feng et al. (2007) studied the phenol degradation in an internal loop airlift bioreactor with yeast *Candida tropicalis*. Their studies mainly focused on the modeling of local dynamic behavior of the reactor and its effect on the phenol biodegradation. Similarly Viggiani et al. (2006) evaluated biodegradation of phenol with *Pseudomonas stutzeri*OX1 in an airlift biofilm reactor of 150 ml capacity. In their study, they observed that the culture took a long period of 7 days for completely degrading phenol with a maximum feed concentration of 450 mg l\(^{-1}\). They also studied substrate inhibition kinetics by fitting the experimental findings to Haldane model.

In general, operating the ILALR in a fed batch mode could rectify the substrate inhibition problems for higher concentrations of toxic compounds, which could not be achieved in batch operation. Quan et al. (2004) studied biodegradation of 2,4-dichlorophenol and phenol in an internal loop airlift bioreactor immobilized with *Achromobacter* sp. In their study they performed the biodegradation of mixed substrate in fed batch and in continuous mode. In the process of fed batch operation with phenol concentration less than 100 mg l\(^{-1}\), removal rate of 2,4-dichlorophenol decreased with increase in the run number, while the phenol degradation rate was just the opposite. Apart from this study, there are no other studies in ILALR pertaining to fed batch biodegradation with the said treatment objective. However, a mixed community of microbes is essential for complete mineralization. Reports on the same employing bioreactor are scant.

Hence the objective of present study is to investigate the performance of an internal loop airlift bioreactor (ILALR) using an indigenous mixed microbial consortium predominantly *Pseudomonas* sp. isolated from sewage treatment plant to degrade phenol and m-cresol as single and dual mixed substrate under batch and fed batch operation.

2. Methods

2.1. Chemicals and reagents

Phenol and m-cresol, used in the study, were of analytical grade; glucose and inorganic salts, used in preparing microbial growth media, were of reagent grade. All the chemicals and agents were purchased from Merck\(^{\text{®}}\), India.

2.2. Microorganism and culture conditions

The microorganism used in this study was a mixed culture capable of degrading phenol and m-cresol. It has been isolated and enriched from a sewage treatment plant located in Guwahati, India. The obtained culture was identified as a mixed culture with predominantly *Pseudomonas* sp., according to the biochemical tests and their results. The culture was cultivated in a 250 ml flask containing 100 ml of Mineral Salt Medium (MSM) in an orbital shaker at 150 rpm and 27 °C. The MSM is composed of (in mg l\(^{-1}\)) (NH\(_4\))\(_2\)SO\(_4\) 230, CaCl\(_2\) 8.0, FeCl\(_3\) 1.0, MnSO\(_4\) - H\(_2\)O 100, MgSO\(_4\) - 7H\(_2\)O 100, K\(_2\)HPO\(_4\) 500, KH\(_2\)PO\(_4\) 250 at pH 7.0 under agitation condition (150 rpm). The culture was then acclimatized over a period of one month to grow in MSM containing phenol and m-cresol as the sole carbon source up to a concentration of 800 mg l\(^{-1}\) and 1000 mg l\(^{-1}\), respectively.

2.3. Biodegradation study in an internal loop airlift bioreactor

An internal loop airlift reactor made of perspex acrylic material with a working volume of 2.5 L was used throughout the study. The reactor consists of two concentric tubes, where the inner tube is removable draft tube (40 × 5 cm), the external tube has dimensions of (60 × 8 cm). The top and bottom of the reactor was sealed with a flange made of stainless steel. All the components used in the reactor were resistant to embrittlement, corrosiveness and swelling due to the phenolics. Also, the material did not yield to the phenolic compounds by way of adsorption. Compressed air from a compressor was fed from the bottom of the reactor via a nozzle of diameter 0.8 cm. Sterile air was fed in the reactor by filtering it through an air filter. The nozzle was placed inside the inner tube and the superficial gas flow was measured with a rotameter. The superficial gas flow was maintained at 2 l min\(^{-1}\) throughout all the experiments. This is an optimal gas flow rate as determined from the hydrodynamic study. No attempts were made to control the temperature inside the reactor however it was monitored to be 26 ± 1 °C.

2.4. Batch biodegradation operation of ILALR

The biodegradation experiments were carried out in batch mode. The reactor (2.5 L capacity) was operated in batch to study the scale-up effect from a shake flask of capacity 100 ml. The batch study was initially done for single substrate degradation study with concentrations of phenol and m-cresol, each 100 mg l\(^{-1}\). The study was repeated with various concentrations of substrates up to a maximum phenol and m-cresol feed concentration 600 mg l\(^{-1}\) and 400 mg l\(^{-1}\), respectively. This was followed by a mixed substrate degradation study where various combinations of phenol and m-cresol concentrations were adopted with a maximum concentration, each 300 mg l\(^{-1}\). Table 1 accounts for the said combinations.

2.5. Fed batch biodegradation operation of ILALR

The reactor was operated in fed batch mode to overcome the degradation problems observed in batch operation. The reactor was initially started in batch mode with a phenol and m-cresol of concentration 100 mg l\(^{-1}\) each in single substrate degradation system and then switched to fed batch mode with a maximum phenol and m-cresol concentration each up to 600 mg l\(^{-1}\), in single substrate system. Similarly dual substrate degradation was also carried out for different feed substrate concentration combinations. The details of fed batch operation adopted in the study are presented in Table 2. In both these studies, a sample of volume 1 ml was collected from the sampling port of the reactor, centrifuged at 10,000g for 3 min and analyzed for concentration of residual phenol/m-cresol and intermediates. All the biodegradation experiments under batch and fed batch operation were carried out until complete degradation of phenol/m-cresol compound is reached.

2.6. Analytical methods

Cell density in the samples was estimated with Diode Array Spectrophotometer (Spekol 1200, Analytik Jena, Germany) by mea-

### Table 1

<table>
<thead>
<tr>
<th>Experimental run no.</th>
<th>Phenol (mg l(^{-1}))</th>
<th>m-Cresol (mg l(^{-1}))</th>
<th>Culture specific growth rate (h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>100</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>200</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>300</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>300</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>300</td>
<td>0.00</td>
</tr>
</tbody>
</table>
suring its absorbance (OD) at wavelength 600 nm. OD_{600} was then converted to dry cell weight by a calibration curve, which was obtained by plotting dry weight of biomass per milliliter of sample vs. OD_{600}. High Performance Liquid Chromatography (Model UV 200 series: Perkin Elmer, USA) was employed to quantify phenol, m-cresol concentrations and intermediates in the biomass free samples. The phenol, m-cresol, hydroquinone, benzoquinone and catechol analysis were performed with C18 column (150 mm × 4.6 mm × 5 μm; Chromotopak) with acetonitrile/water (60/40) as the mobile phase at a flow rate of 1 ml min⁻¹, and the detection was done with a UV detector set at 275 nm. The retention periods for phenol and m-cresol were 2.75 min and 3.25 min, respectively. For determination of organic acids, Acclaim OA column of Dionex (150 mm × 4.0 mm × 5 μm) was employed with 100 mM Na₂SO₄, pH 2.65 adjusted by using methanesulfonic acid as mobile phase at a flow rate of 0.6 ml min⁻¹ and the detection was done with a UV detector set at 210 nm.

### Table 2

Concentrations of the phenolics in single substrate and dual substrate system along with volume treated in each step in the ILALR operated under fed batch mode

<table>
<thead>
<tr>
<th>Step</th>
<th>Phenol concentration (mg l⁻¹)</th>
<th>m-Cresol concentration (mg l⁻¹)</th>
<th>Volume treated (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single substrate system</td>
<td>Dual substrate system</td>
<td>Single substrate system</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>100</td>
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<td>300</td>
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<td>300</td>
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<tr>
<td>4</td>
<td>400</td>
<td>300</td>
<td>400</td>
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<tr>
<td>5</td>
<td>600</td>
<td>–</td>
<td>600</td>
</tr>
</tbody>
</table>

3. Results and discussion

#### 3.1. Batch biodegradation of phenol in the ILALR

It was observed from the biodegradation time profile that phenol at concentrations 100, 200, 300, 400 and 600 mg l⁻¹ were completely degraded by the culture within 10, 15.3, 17, 27.3 and 47 h, respectively. The results clearly showed good ability of the reactor in degrading phenol even at fairly high concentration employing the *Pseudomonas* sp., as opposed to the study by Viggianni et al. (2006) who required nearly 7 days to degrade phenol at a maximum feed concentration 450 mg l⁻¹ in an airlift reactor using *Pseudomonas stutzeri* OX1. The present study also revealed a substrate inhibition pattern due to phenol on the culture biomass growth, in line with our earlier batch shake flask study. An increase in phenol feed concentration up to 300 mg l⁻¹ enhanced the specific growth rate of the culture, however the concentration above 300 mg l⁻¹ shows a declining value of the growth rate. Fig. 1 shows the biomass output profile as a function of phenol feed concentration. The specific degradation rate of the system was also calculated in addition to culture specific growth rate. In both the cases the substrate inhibits at a phenol feed concentration of 300 mg l⁻¹. This observation is similar to that of shake flask study (Saravanan et al., 2008). Viggianni et al. (2006) also observed that substrate inhibition commences at phenol concentration of 200 mg l⁻¹. Furthermore, to study the effect of scale-up from the batch shake flask to reactor, the calculated specific growth rate (μₚ) data were fitted to the Haldane's substrate inhibition model (Kumar et al., 2005).

The model equation was solved using non-linear regression technique in MATLAB® 7.0 and the biokinetic parameters were evaluated. It was observed from the estimated biokinetic parameters that the value of maximum specific growth rate (μₚ_max) is 0.48 h⁻¹ and other parameters like Kᵣ and Kᵢ were found to be 171.2 mg l⁻¹ and 294.7 mg l⁻¹, respectively. In comparison to our previous batch shake flask study (Saravanan et al., 2008) the estimated values are found to be high except that of Kᵢ. Among these three parameters, μₚ_max is having highest significance, since it represents the culture growth for the given concentration of substrate. In other words, it is the potential of the system in degrading the substrate effectively. Moreover the present study mainly focused on the wastewater treatment where growth parameter defines the efficiency of plant. Higher growth rate denotes the potential of the ILALR system in degrading phenol using *Pseudomonas* sp.

#### 3.2. Batch biodegradation of m-cresol in ILALR

The batch degradation study was also carried out in ILALR with m-cresol as a substrate. Fig. 2 shows the biodegradation profile of m-cresol as a function of time. It could be observed from the figure that the culture could degrade a minimum m-cresol feed concentration of 100 mg l⁻¹ and maximum m-cresol feed concentration of 400 mg l⁻¹ in 10 h and 36 h, respectively. Similarly the biomass output was also shown in Fig. 3. It was observed from the study that the system failed to degrade the substrate with concentration above 400 mg l⁻¹ whereas in shake flask study it degraded a maximum concentration of 900 mg l⁻¹. Nevertheless, both shake flask and ILALR studies show similar substrate inhibition at 200 mg l⁻¹. The reason for the failure of the system could be explained by estimating the biokinetic parameters. Hence the biokinetic parameters were estimated in similar way by fitting it to Haldane's model. The modeling yielded the following parameter values: μₚ_max = 0.185 h⁻¹; Kᵣ = 65.1 mg l⁻¹ and Kᵢ = 243.56 mg l⁻¹. The ILALR study has same Kᵣ and Kᵢ values while μₚ_max is found to be very low. The μₚ_max estimated from Haldane model, showed that the scale-up from batch to ILALR has affected the degradation capability of the culture. Although the system has a good geometry for mixing and dissolved oxygen, the toxicity of the m-cresol affected the system scale-up performance.
3.3. Batch biodegradation of phenol and m-cresol as dual substrate system

The phenol and m-cresol were degraded in the ILALR as a dual substrate system. From the results of the single substrate degradation study in the ILALR, it was found that m-cresol inhibited the growth of the culture at concentration of 200 mg l\(^{-1}\) and above, and phenol inhibited the culture growth at 300 mg l\(^{-1}\) and above. Based on these results, following concentration ranges for phenol and m-cresol were chosen in this multisubstrate degradation study–between 100 and 300 mg l\(^{-1}\) of phenol, between 100 and 300 mg l\(^{-1}\) of m-cresol. Table 2 shows the design matrix of concentration employed in the study.

Fig. 4 shows the degradation profile of these two substrates in the dual substrate system. As observed from the figure, irrespective of the concentration levels of the compounds, phenol was preferentially degraded over m-cresol. This may be due to the fact that phenol, compared to m-cresol, is a much simpler carbon source and therefore is easily consumed by the mixed culture, an observation already reported in the earlier m-cresol batch shake flask study (Saravanan et al., 2008). However with low phenol concentrations (100–200 mg l\(^{-1}\)), rate of m-cresol biodegradation was enhanced, whereas with phenol concentration above 200 mg l\(^{-1}\) the culture failed to degrade the substrates. This may be due to the sum of concentration effect (Fig. 4).

Growth pattern of the culture in presence of both phenol and m-cresol in the media differed quite largely from that of the single substrate study. This is quite obvious due to availability of more carbon source in this multisubstrate system. The cell growth curves at all phenol and m-cresol feed concentrations are presented in the form of biomass concentration (mg l\(^{-1}\)) illustrated in Fig. 5. It could be observed from the figure that the culture took more time to grow when m-cresol was present in the media (together with phenol), however, the cell mass output was also high in such cases (Bai et al., 2007).

Table 1 presents the estimated specific growth rate for various combinations of phenol and m-cresol in this dual substrate degradation study. The table shows that substrate inhibition on the culture growth is evident in the low concentration range for the ILALR study.

3.4. Sum kinetics model fitting of experimental specific growth rate

Experimental data on specific growth rates of the culture was fitted to the sum kinetics model proposed by Yoon et al. (1977) to predict its variations due to various combinations of concentrations of substrates: phenol and m-cresol. This model also used for
evaluation of the interaction between phenol and m-cresol on the growth of the culture, and to estimate the relative effects of the two substrates on their individual uptakes (degradation of phenol and m-cresol). The form of this model is shown in equation:

\[
\mu = \frac{\mu_{\text{max},1} S_{1L}}{K_{S,1} + S_{1L} + \frac{S_{2L}}{I_{12}} I_{21} S_{2L}} + \frac{\mu_{\text{max},2} S_{2L}}{K_{S,2} + S_{2L} + \frac{S_{1L}}{I_{21}} I_{12} S_{1L}}
\]  

(1)

The model equation is almost similar to that of Haldane’s with an additional interaction parameter. The interaction parameter \(I_{ij}\) indicates the degree to which substrate \(i\) affects the biodegradation of substrate \(j\); a large value of the parameter indicates a strong inhibition on the substrate uptake by the microorganism (Yoon et al., 1977). The other kinetic parameters \(\mu_{\text{max}}, K_s, K_i\) in the equation are the same as those for any single substrate system. A non-linear regression technique involving constraints for positive integer values of the parameters was employed for solving the model equation using MATLAB® 7.0. Very high determination coefficient \((R^2)\) value (0.98) was obtained by fitting the model equation to the experimental growth rate values of the culture. The interaction parameters \((I_j)\) values were found to be 9.9 for \(I_{\text{phenol–m-cresol}}\) and 3.9 for \(I_{m\text{-cresol–phenol}}\) respectively. While the interaction parameter \(I_{\text{phenol–m-cresol}}\) represents the effect of phenol on m-cresol degradation with respect to the specific growth rate; the other interaction parameter \((I_{m\text{-cresol–phenol}})\) represents the effect of m-cresol on phenol degradation. From the values of these parameters, it could be concluded that phenol at 100 mg l\(^{-1}\) exhibits stronger inhibition on m-cresol degradation, than that of the vice versa. In literature, a maximum interaction parameter value of 5.16 was reported for the effect of toluene on benzene degradation by a Pseudomonas putida strain (Abuhamed et al., 2004). Considering the fact that phenol is comparably simpler carbon source than m-cresol and thus easily assimilable substrate, a large value of its inhibitory effect on m-cresol degradation is quite justifiable. The interaction parameter values obtained from the model render a fair knowledge on the inhibitory effects of dual substrate degradation.

Even though the batch operation of ILALR in degrading phenolics yields good performance up to certain concentrations, it fails to yield a satisfactory performance at higher concentrations of substrate. This shortcoming was rectified by operating the reactor in fed batch mode.

3.5. Fed batch biodegradation of single substrate in ILALR

Fig. 6 shows the removal of phenol and m-cresol as a single substrate in a fed batch operated ILALR. It was observed that both the substrates were completely degraded by the culture within 26 h and 36 h, respectively. Initially the reactor was operated with a lower substrate concentration of 100 mg l\(^{-1}\) each, which was degraded in 6 h (for both the cases of phenol and m-cresol) and later the substrate was increased step by step from 100 to 200, 300, 400 mg l\(^{-1}\) and finally to 600 mg l\(^{-1}\). Hence, operating in fed batch mode actually took only 20 h and 30 h for complete degradation of the phenolics of the said concentration. Moreover it was observed that when compared with simple batch mode, the degradation time was very less in the fed batch mode even with higher concentrations. It was observed that under simple batch operation, the reactor could not degrade the substrate beyond a concentration 400 mg l\(^{-1}\). This shortcoming was overcome in the study by employing fed batch operation and that too reasonably faster and at high feed concentration (10 h for 600 mg l\(^{-1}\) of m-cresol). The study also yielded maximum output of biomass that confirms the effective uptake of the phenolics by the culture.

The specific degradation rate \((q)\) of the system was also calculated, since the present study mainly focuses on the degradation of the phenolics. The specific degradation rates were presented as function of initial concentrations of phenol and m-cresol. The specific degradation rate was calculated by the following equation:

\[
q = \frac{-1}{X} \frac{dX}{dt} + \frac{F}{V}
\]

(2)

where \(F\) = feed flow rate of MSM with substrate into the reactor (l h\(^{-1}\)), \(V\) = volume of the reactor (ml). A substrate inhibition concentration in the degradation rate was also obtained that is same as that of batch study i.e. 200 mg l\(^{-1}\) for both the substrates.

3.6. Biodegradation of phenol and m-cresol as dual substrate system in fed batch operated ILALR

The biodegradation of phenol and m-cresol as dual substrate system in the bioreactor was studied under its fed batch mode of operation and is shown in Fig. 7. It can be seen that first run i.e., phenol and m-cresol of feed concentration 50 mg l\(^{-1}\) each were completely degraded with in 7 h. In the second run, for a concentration of 100 mg l\(^{-1}\) of each of the substrates, phenol was degraded relatively faster i.e. within 4 h while m-cresol was degraded relatively slower i.e. within 5 h. In both these
cases, no lag phase was observed in their degradation profiles. In the third step, the reactor was operated with a concentration of 200 mg l\(^{-1}\) for each of the substrates, and it was observed that the phenol was preferentially degraded rather than m-cresol and it took 6.3 h to degrade phenol. On the other hand, it took 7.3 h to degrade m-cresol. At the final step, the substrate concentrations were increased to 300 mg l\(^{-1}\) for each substrate where a short lag period of 3 h was observed in case of m-cresol only. Moreover the substrates were completely degraded in 10.3 h. It was observed that, unlike a simple batch operation in ILALR, the higher concentrations of substrates were completely degraded in the fed batch operation. Overall in all these steps, no lag phase was observed in the degradation profile of phenol and it was preferentially degraded over m-cresol. The degradation rates of both the substrates in various runs are presented in Table 3.

It was found that the failures observed in the batch operation were overcome in the fed batch mode operation where complete degradation of the phenolics is possible in a much shorter period without any lag in the degradation profile for phenol. 

Quan et al. (2004), in their biodegradation study of 2,4-dichlorophenol and phenol in an airlift reactor immobilized with \textit{Achromobacter} sp., observed that the degradation rate involving 2,4-dichlorophenol decreased with increase in their experimental runs while that of phenol was found to be enhanced. But in their study the concentration variations in each step were less than 100 mg l\(^{-1}\) and it took 6.3 h to degrade phenol. On the other hand, it took 7.3 h to degrade m-cresol. At the final step, the substrate concentrations were increased to 300 mg l\(^{-1}\) for each substrate where a short lag period of 3 h was observed in case of m-cresol only. Moreover the substrates were completely degraded in 10.3 h. It was observed that, unlike a simple batch operation in ILALR, the higher concentrations of substrates were completely degraded in the fed batch operation. Overall in all these steps, no lag phase was observed in the degradation profile of phenol and it was preferentially degraded over m-cresol. The degradation rates of both the substrates in various runs are presented in Table 3.

It was found that the failures observed in the batch operation were overcome in the fed batch mode operation where complete degradation of the phenolics is possible in a much shorter period without any lag in the degradation profile for phenol. 

Overall results obtained in the present ILALR system operated under fed batch mode showed better performance in degrading phenol and m-cresol. But a treatment plant operated under continuous mode is more suited. A study pertaining to this objective has already been initiated by the authors’ research group.

### 4. Conclusions

The results revealed that an indigenous mixed culture predominantly \textit{Pseudomonas} sp. has good potential in degrading phenolic compounds. The study also showed that scale-up of the above degradation process is highly effective. A sum kinetics model rendered better understanding of the inhibitory effect of the substrates on the culture growth for dual substrate study. In fed batch operations phenol and m-cresol was found to be consumed by the culture completely in a short period. As a whole the present study showed that the performance of internal loop airlift bioreactor in treating industrial wastewater containing phenolic compounds is enhanced by using mixed culture consortium predominantly \textit{Pseudomonas} sp.

### References


